Investigation of bending strength and modulus of elasticity of a new type of black locust plywood for construction

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Abstract: *The mechanical properties bending strength and modulus of elasticity in bending of a new type plywood for construction, based on black locust wood, have been investigated in relationship with the bonding technological factors. The experimental investigation is based on an optimal composite design with four control factors – temperature, pressure, bonding duration and specific glue consumption. Regression models describing the dependence of bending strength and modulus of elasticity in bending on the investigated technological bonding parameters are estimated. The obtained experimental and model-based results are analysed and discussed.*
Keywords*: CONSTRUCTION, WOOD, PLYWOOD, BENDING STRENGTH, MODULUS OF ELASTICITY IN BENDING, MATHEMATICAL MODELING, BLACK LOCUST (ROBINIA PSEUDOACACIA).*

1. Introduction

Wood is one of the most popular and widely used building materials, with the construction sector being the largest consumer of wood and timber. Its use as a building material is exclusively due to the large number of the positive properties of wood materials [1-4]: relatively low bulk density, easy machinability, significant compressive and tensile strength, low thermal conductivity and others. Last but not least are the positive environmental aspects and the possibility for recovery and renewal of wood resources.

At the same time, the plant origin of wood determines many disadvantages - anisotropic structure, hygroscopicity and the associated variability of shape and size, resistance to various biological attacks and the ability to burn. The modern woodworking industry has accumulated centuries of experience in solving the problems of wood deficiencies. On the one hand, technologies have been developed to protect and modify wood in order to increase its durability and reduce its hygroscopicity and flammability, as well as to increase some of its strength characteristics. The other increasingly fast-growing direction, which eliminates the shortcomings of wood and adds new properties, is the development of wood composite materials, which are increasingly used in construction.

Such wood composite material is plywood, which is most widely used in construction. The main tree species on which plywood production in Bulgaria is based in recent years are poplar and beech. The stocks of raw materials of these types, suitable for plywood production, are constantly decreasing, and at the current rate of exploitation of the forests, the stocks of beech will disappear in the next 2-3 decades, and the stocks of poplar are already running out. This makes it necessary to look for opportunities for the production of plywood from other wood species, from which there are stocks of wood. Such a tree species for our country is the black locust (*Robinia pseudoacacia*), from which there are significant stocks of wood, which so far do not find wide economic application.

The main goal of the present work is to determine the modulus of elasticity in bending and bending strength and to investigate the influence of the main technological bonding factors on these two indicators for a new type of plywood for construction, made of black locust wood.

2. Experimental results and analysis

The materials needed for the research were black locust veneer with a nominal thickness of 2.2 mm and water-soluble phenol-formaldehyde adhesive. These materials were used for the production in laboratory conditions of six-layer, black locust, waterproof plywood for construction with a nominal thickness of 12 mm.

The current investigation aims to establish the influence of the main technological factors in bonding on the modulus of elasticity in bending and bending strength.

The first factor (z_1) is the temperature of the press platens. The range of its variation was determined according to the manufacturer's recommendations in the interval from 120˚C to 160˚C.

The second factor (z_2) is the specific pressure. The interval of its variation was determined by recommendations in the specialized literature. The levels of variation are 1 MPa, 1.5 MPa and 2 MPa.

The third factor (z_3) is the duration of plywood pressing. The range of its variation was determined according to the recommendations of the adhesive manufacturer and from the recommendations for the duration of plywood pressing given in the specialized literature. The levels of variation are as follows: 8 min; 11 min and 14 min.

For fourth factor (z_4) is the specific glue consumption (specific cost). The range of its variation was determined according to the recommendations of the adhesive manufacturer and from the recommendations for specific glue consumption given in the specialized literature. The experimental region for the specific glue consumption is from 100 g/m^2 to 200 g/m^2.

The chosen experimental design was optimal composite design [5] with four control factors: temperature of press plates, pressure, specific glue consumption and duration of pressing. The number of experimental runs in the experimental design is 24. Additional (repeated) three experiments have been made at the central point of the design, where all factors are set equal to the values in the middle of their variation region. Six measurements the mechanical properties of obtained black locust plywood plates the modulus of elasticity in bending (y_1) and bending strength (y_2) are performed for each experimental run and the results are averaged. Thus, the total number of conducted measurement tests is 162.

Table 1. *Data from repeated observations.*

	Elasticity in bending y_1	Bending strength y_2
Mean value	14218.70 N/mm^2	124.86 N/mm^2
St. deviation	458.39 N/mm^2	8.27 N/mm^2

The results for the means and the standard deviations from the repeated experimental runs in the at the central point of the design at constant levels of the process parameters: the temperature of the press platens z_1 = 140 ˚C, specific pressure z_2 = 1.5 MPa, duration of plywood pressing z_3 = 11 min and specific glue consumption z_4 = 150 g/m^2 are presented in Table 1.

The determination of the modulus of elasticity in bending and bending strength was performed according to the standard BDS EN 310: 1999 Wood based panels: Determination of the modulus of

elasticity in bending and bending strength [6]. This European Standard describes the method for determining the modulus of elasticity in bending and bending strength of wood - based panels with a nominal thickness equal to or greater than 3 mm.

3. Model-based investigation results

Regression models are estimated the modulus of elasticity in bending (y_1) and bending strength (y_2) of the produced black locust plywood plates as a function of the temperature of the press platens (x_1), the specific pressure (x_2), the duration of plywood pressing (x_3) and the specific glue consumption (x_4) in coded in the region [-1 ÷ 1] units [7]. The relation between coded (x_i) and natural (z_i) units can be expressed by the equation:

$$x_i = (2z_i - z_{i,max} - z_{i,min})/(z_{i,max} - z_{i,min}). \quad (1)$$

where $z_{i,max}$ and $z_{i,min}$ are the maximal and the minimal values, determined by the experimental regions of each of the investigated process parameters. The regression models, together with the determination coefficients are presented in Table 2.

Table 2. *Regression models.*

	Regression models	***R^2, %***
y_1	$y_1 = 12002.53 - 1052.90x_1 - 193.13x_2 + 774.01x_4 - 1577.36x_1^2 + 903.95x_3^2 + 1111.56x_4^2 - 297.49x_1x_2 + 211.18x_3x_4 + 259.65x_1x_4 + 1273.47x_1x_2^2 - 256.87x_1x_2x_4 - 569.71x_1^2x_4$	90.92
y_2	$y_2 = 138.70 - 12.06x_1 + 4.40x_4 + 6.88x_1^2 - 18.38x_4^2 - 4.55x_1^2x_2 + 3.11x_2x_3 + 2.88x_2x_4 + 13.28x_1x_2^2 - 3.61x_1x_2x_3 + 4.72x_1x_2x_4 + 2.20x_2x_3x_4$	85.94

The goodness of fit tests and the values of the determination coefficients show good prediction characteristics of the estimated models. They can be used for the choice of appropriate process parameters under given technological requirements for the modulus of the elasticity in bending (y_1) and the bending strength (y_2) during the production of black locust plywood.

The estimated regression models are used for the investigation of the dependencies of the modulus of the elasticity in bending (y_1) and the bending strength (y_2) of the produced black locust plywood plates as on the variation of the process parameters: the temperature of the press platens (z_1), the specific pressure (z_2), the duration of plywood pressing (z_3) and the specific glue consumption (z_4), visualized on the contour plots in Fig. 1 – Fig. 4.

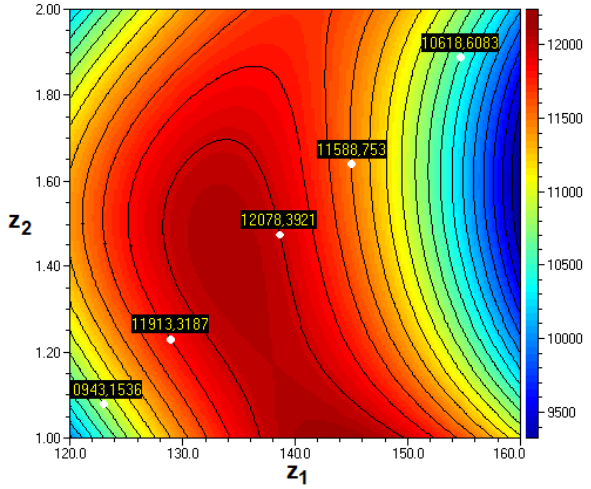

Fig. 1 *Contour plot of the bending elasticity (y_1) vs. the temperature of the press platens (z_1, ˚C) and the specific pressure (z_2, MPa) for z_3 = 11 min and z_4 = 150 g/m^2.*

In Fig. 1 the contour plot of the elasticity in bending (y_1) as a function of the temperature of the press platens (z_1,˚C) and the specific pressure (z_2, MPa), for constant values of the duration of plywood pressing (z_3) and the specific glue consumption (z_4): z_3 = 11 min and z_4 = 150 g/m^2. It can be seen that under the specified conditions, the factor with larger influence is the temperature of the press platens (z_1). The region, where the maximal values of the elasticity in bending (y_1) can be obtained for temperatures of the press platens (z_1) in the region from 132˚C to 146˚C and specific pressure values below 1.6 MPa.

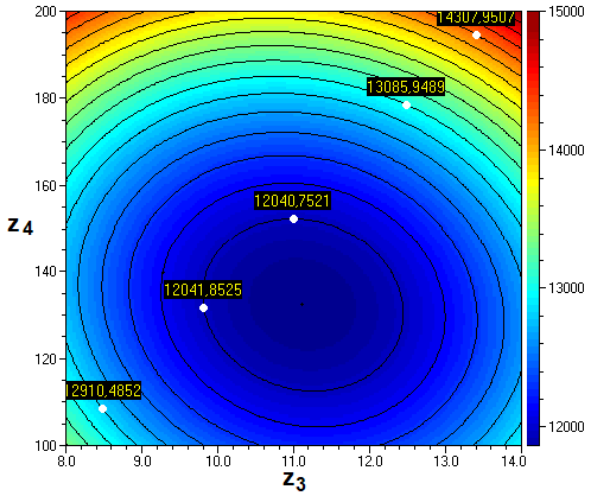

Fig. 2 *Contour plot of the bending elasticity (y_1) vs. the duration of plywood pressing (z_3, min) and the specific glue consumption (z_4, g/m^2), for z_1 = 140 ˚C and z_2 = 1.5 MPa.*

Fig. 2 presents the contour plot of the bending elasticity (y_1) as a function of the duration of plywood pressing (z_3, min) and the specific glue consumption (z_4, g/m^2), for constant values of the temperature of the press platens and the specific pressure, z_1 = 140 ˚C and z_2 = 1.5 MPa. It can be seen that the highest values of the bending elasticity are obtained for the highest values of the specific glue consumption z_4 > 190 g/m^2 for the set by factors z_1 and z_2 conditions.

The contour plot of the dependence of the bending strength (y_2) on the temperature of the press platens (z_1,˚C) and the specific pressure (z_2, MPa) for constant values of the duration of plywood pressing (z_3) and the specific glue consumption (z_4): z_3 = 11 min and z_4 = 150 g/m^2 is presented in Fig. 3. The maximal values of the bending strength in this case are obtained for lowest values of the temperature of the press platens around 120˚C and specific pressure in the region 1.3 ÷ 1.5 MPa.

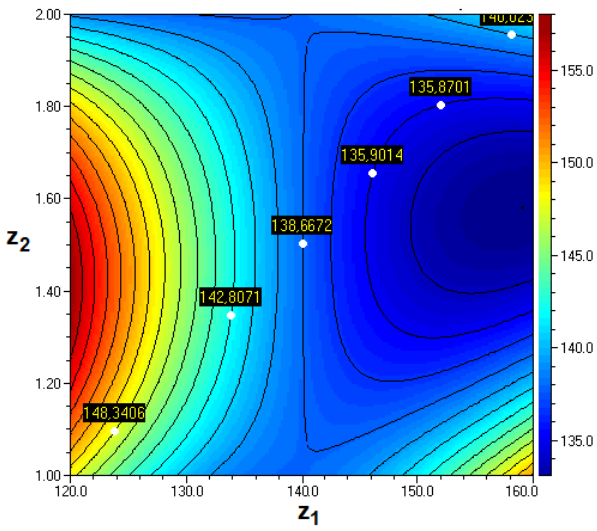

Fig. 3 *Contour plot of the bending strength (y_2) vs. the temperature of the press platens (z_1, ˚C) and the specific pressure (z_2, MPa) for z_3 = 11 min and z_4 = 150 g/m^2.*

In Fig. 4 is presented the contour plot of the bending strength (y_2) vs. the duration of plywood pressing (z_3, min) and the specific glue consumption (z_4, g/m^2), for constant values of the temperature of the press platens and the specific pressure, z_1 = 140 ˚C and z_2 =

1.5 MPa. It can be seen, that under the set conditions, the bending strength (y_2) is not dependent on the duration of plywood pressing (z_3, min), while the choice of the specific glue consumption (z_4, g/m^2) is important and for obtaining the maximal values of the bending strength, the specific glue consumption should be set in the region 150 ÷ 160 g/m^2.

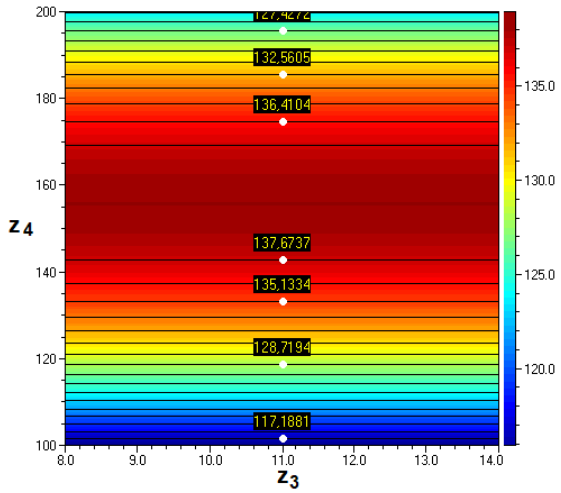

Fig. 4 *Contour plot of the bending strength (y_2) vs. the duration of plywood pressing (z_3, min) and the specific glue consumption (z_4, g/m^2), for z_1 = 140 °C and z_2 = 1.5 MPa.*

From the obtained investigation results is seen that the changes of all factors influence the values of the investigated mechanical properties - the modulus of elasticity in bending (y_1) and bending strength (y_2) of the produced black locust plywood plates. The choice of optimal regimes should be performed at defining concrete technological requirements for all quality characteristics simultaneously.

Experimental studies on the modulus of elasticity in bending and bending strength for construction black locust plywood bonded with phenol-formaldehyde adhesive confirm the patterns and trends of previous studies on the same properties but for black locust plywood [bonded with urea-formaldehyde]. Both indicators depend very much on the wood species from which the plywood is made, and in both studies the respective black locust plywood is superior in values to the respective beech and poplar plywood. This is due to the higher mechanical properties of black locust wood, compared to the same for beech and poplar. Technological factors in gluing also have a decisive influence on the values of the two indicators, as the temperature of the press platens and the specific glue consumption are formed as slightly more important for the final results.

4. Conclusions

The current investigation aims to establish the influence of the main technological factors in bonding on the modulus of elasticity in bending and bending strength.

For the experimental investigation an optimal composite design is realized with four control factors: temperature of press plates, pressure, specific glue consumption and duration of pressing. The number of experimental runs in the experimental design is 24 and 3 additional experiments have been made at the central point of the design. Six measurements the mechanical properties of obtained black locust plywood plates the modulus of elasticity in bending (y_1) and bending strength (y_2) are performed for each experimental run. Thus, the total number of conducted measurement tests is 162.

Regression models for the modulus of elasticity in bending (y_1) and bending strength (y_2) of the produced black locust plywood plates are estimated as a function of the temperature of the press platens (x_1), the specific pressure (x_2), the duration of plywood pressing (x_3) and the specific glue consumption (x_4). The obtained dependencies of the two quality characteristics on the process parameters are used for investigation and prognostication.

Research confirms the good prospects for the introduction of this new type of plywood in construction.

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References

1. G. Blaskova, Properties and use of black locust wood. *Furniture and woodworking industry* (Sofia) 3 (2000)
2. G. Blaskova, *Wood Science* (Publishing house at LTU, Sofia, 2003)
3. P. Panayotov and team, Report on the topic: "Comparative studies of the properties of the wood of the straight black locust Robinia pseudoacacia forma rectissima and the traditionally used white acacia Robinia pseudoacacia L.". MES, FSI at LTU-Sofia, PSIL for wood modification, Sofia, (2004)
4. A. Hristov, Sci. researches of the Union of Scientists in Bulgaria - Plovdiv. Series C. Tech. and Technol., **V**, Balkan Conf. of Young Scient. (Plovdiv) 39-46 (2005)
5. I. Vuchkov, *Experimental research and identification* (Technique, Sofia, 1990)
6. BDS EN 310: 1999 "*Wood-based panels. Determination of the modulus of elasticity in bending and bending strength*".
7. *QstatLab home page*: http://www.qstatlab.co.uk/eng/index.html